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Electronic Chart Display and Information System (ECDIS) Test and Evaluation, Summary Report

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16. Abstract

This summary report describes four sea trials and one man-in-the-loop simulator experiment conducted by the U.S. Coast Guard Research and Development Center from 1990 to 1993 to thoroughly test and evaluate the adequacy of the International Maritime Organization's Performance Standard for ECDIS. Issues examined include: the contribution to safety of navigation, the effects of the navigation workload, features and functions required during route monitoring, and the contribution of integration with radar.

Each of the five tests were designed to incorporate known methodology and advanced technology to thoroughly test the contributions that ECDIS might make to the operational practices on a ship's bridge. As the experiments progressed, the technology became more sophisticated, with information being sought in more breadth and depth. Each experiment, building on the findings of the previous, was designed to ask more indepth questions, to gain more complete information. This four-year effort is one of the most comprehensive studies done on ECDIS performance.

There are serveral key findings produced by this body of work. It was shown consistently that ECDIS can provide equivalent or greater safety than the paper chart and more traditional methods of navigation. Another key finding is that navigation workload is reduced, allowing the mariner to concentrate on collision avoidance or other tasks of similar importance. In the area of user-interface design, it was found that the mariner wanted an "uncluttered" display during route monitoring, with more features immediately available if needed.

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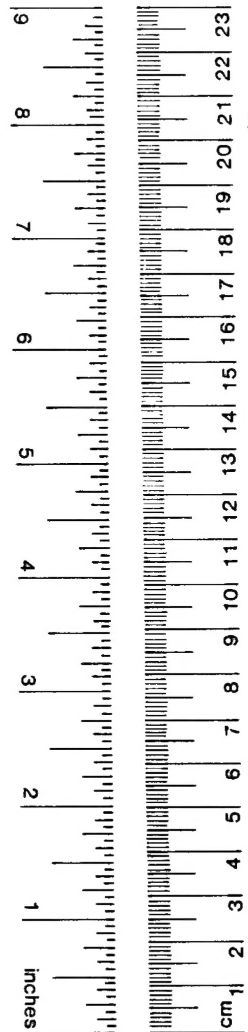
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

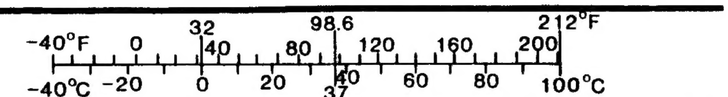


TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

PAGE

EXECUTIVE SUMMARY

In the last few years, the Electronic Chart Display and Information System (ECDIS) has emerged as a powerful addition to the modern bridge, offering the possibility of effecting major changes in the navigation process while improving the safety and efficiency of maritime operations. By superimposing electronic chart, ship's position, and RADAR on one display, ECDIS has the potential to improve the accuracy of navigation, increase awareness of dangerous conditions, and reduce the mariner's workload. An ECDIS is defined by the International Maritime Organization (IMO) as a system which is compliant with the IMO Performance Standards for ECDIS. Systems which are not "IMO compliant" are categorized as Electronic Chart Systems (ECS).

There is a worldwide effort to study this new and promising technology. The International Maritime Organization and the International Hydrographic Organization (IMO/IHO) Harmonization Group on ECDIS (HGE) began the process of developing a draft performance standard for ECDIS (IMO/IHO, 1989 & 1992). This performance standard was completed and adopted by IMO under Resolution A817 in November 1995. This report describes the United States Coast Guard's (USCG) four year effort to examine potential effects of ECDIS both at-sea and in a full-mission ship's bridge simulator. The results and insights garnered from these studies contributed to U.S.A. position reports on the IMO Performance Standard for ECDIS. These various position reports were provided to the IMO Safety of Navigation Subcommittee from 1991 to 1995.

The USCG developed a program to thoroughly test the adequacy of the Performance Standards for ECDIS. This program consisted of four sea trials and one man-in-the-loop simulator experiment (Table ES.1 summarizes the experiments for the U.S. Test and Evaluation Program). This report discusses the background, experimental design, instrumentation, results and conclusions of the following experiments.

OCTOBER 1990 INITIAL SEA TRIALS - Confined waterway/harbor navigation tests conducted on board the U.S. Merchant Marine Academy T/V KINGS POINTER. Mariner performance was evaluated in terms of deviation from intended track (XTD)***(see table ES.1)***. The subjects were one master and one cadet on an established route with predetermined turns and waypoints. Deviation from intended track (cross track distance or XTD) was monitored. Results indicated that *overall track keeping performance significantly improved when navigating with ECDIS.*

OCTOBER 1991 KINGS POINTER SEA TRIALS - Confined waterway/harbor navigation tests conducted on board the U.S. Merchant Marine Academy T/V KINGS POINTER on the East River in New York***(see table ES.1)***. Building on 1990 Sea Trials, Mariner performance was again evaluated in terms of deviation from intended track (XTD). The subject pool consisted of 20 Mariners: 4 pilots, 5 masters, 4 mates and 7 cadets. Results of these trials

indicated that overall navigational performance of mariners is significantly enhanced when using ECDIS. Additionally, *no significant differences were found in navigational performance between varying experience levels of mariners while navigating with ECDIS*.

SEPTEMBER - OCTOBER 1992 SIMULATOR EXPERIMENTS - A series of simulator experiments were conducted at Marine Safety International/Computer Aided Operations Research Facility (MSI/CAORF). Experimental scenarios consisted of port arrivals and departures with one mariner alone on the bridge responsible for navigation, collision avoidance, and bridge management tasks. The simulator provided an environment to test mariners under stress, without the danger of an accident. The subject pool consisted of six expert mariners, four masters and two mates. Test results indicated that *ECDIS increased navigation safety* both by improving the accuracy of ship tracks and by allowing the mariners to spend a greater proportion of time on collision avoidance. With automatic updating of position, *ECDIS decreased the workload* for navigation. Without automatic updating of position, ECDIS became ineffective. Mariners expressed a *preference for a relatively simple chart* display for route monitoring, with the immediate availability of a larger set of features. *No measurable effects of RADAR features on ECDIS* were found, although mariners felt that this should be a valuable addition.

TABLE ES.1 - SUMMARY OF U.S. EXPERIMENTS

DATE	TYPE	MARINERS	ECDIS *
October 1990 2 days	Sea Trials T/V KINGS POINTER	1 Master 1 Cadet	1) NavGraphic II: Trimble Navigation
October 1991 8 days	Sea Trials T/V KINGS POINTER	4 Pilots 5 Masters 4 Mates 7 Cadets	1) PINS 9000: OSL
Sep - Oct 1992 30 days	Ashore Simulator MSI/CAORF	4 Masters 2 Mates	1) PINS VME: OSL 2) Disk Navigation Sys: Robertson
Jan - Feb 1993 18 days	Sea Trials USCG Cutter BITTERSWEET	7 Qualified Officers of the Deck (OOD)	1) ECPINS: OSL
March - April 1993 10 days	Sea Trials M/V KINGS POINTER	4 Pilots 4 Masters 5 Mates	1) ECPINS OSL 2) Hydraut EC Series R&H 3) ATLAS 9800 Atlas Electronik

* Note: ***Any mention of a manufacturer or product in this report is not intended as an endorsement by the U.S. Coast Guard, but rather as an acknowledgement that the system cited was used in conjunction with the U.S. ECDIS Test and Evaluation Program.***

JANUARY - APRIL 1993 BITTERSWEET & KINGS POINTER SEA TRIALS - Two sets of sea trials were conducted back to back. The first trials were designed to closely monitor mariners as they used ECDIS during normal at-sea conditions. The trials consisted of harbor and coastal navigation trials during January and February 1993 aboard the USCG Cutter BITTERSWEET, a 180' (55m) ocean-going buoy tender. All of the ship's seven qualified officers of the deck (OODs) participated as test subjects. Three of the OODs were senior watchstanders and four were junior watchstanders. Extensive ship control data were recorded, and a variety of human factors techniques were used to measure performance, workload and operator reactions. The second sea trials were conducted aboard the new U.S. Merchant Marine Academy training vessel, M/V KINGS POINTER. Thirteen experienced mariners participated in the trials in the upper East River/Manhasset Bay, New York area: four pilots, four masters and five mates.

Following the underway period, mariners completed a written questionnaire and then were verbally debriefed. Results of the debriefing as well as other data indicated that *navigation workload decreased when using ECDIS.* The mariners felt that the ECDIS *display must be simple and uncluttered,* ***but all other relevant navigational information must be readily available***. Mariners felt ECDIS made an *excellent contribution to safe navigation* and that a *fully capable, fully integrated RADAR/ARPA is necessary for navigation and collision avoidance, and poses no loss in capability.* Mariners indicated that since all three ECDIS devices had very different user-interfaces, a *minimum number of standard functions should be designed into ECDIS specifications* to help prevent operator errors due to unfamiliar interfaces.

Each test was designed to incorporate known methodology and advanced technology to thoroughly evaluate the Draft Performance Standard for ECDIS. As the experiments progressed, the technology became more sophisticated, with information being sought in more breadth and depth. Each experiment, building on the findings of the previous, was designed to ask more indepth questions, to gain more complete information. The result of this was one of the most comprehensive studies done on ECDIS performance.

The USCG IMO/IHO HGE representative for ECDIS standards development used the findings from the October 1991 Sea Trials to develop a position paper on several of the ECDIS Provisional Performance Standard Issues. This position paper along with other member nations recommendations were combined to create an IHO/IMO HGE Draft Performance Standard for ECDIS (IHO/IMO, Sep 1992). Insight and recommendations based on the later experiments were used to improve the IMO Draft Performance Standard for ECDIS, which became MSC/Cir. 637(IMO, May '94).

There are several key findings produced by this body of work. It has shown consistently that ECDIS can provide equivalent or greater safety than that provided by the use of paper chart and more traditional methods of navigation. Another key finding is that navigation workload

is reduced, allowing the mariner to concentrate on collision avoidance and/or other tasks of similar importance. In the area of user-interface design, it was found that the mariner agreed for the most part with the Draft Performance Standard for ECDIS. They wanted an "uncluttered" display during route monitoring, with more features immediately available if needed. The findings, however, did suggest several places where the Draft Performance Standard for ECDIS were lacking. These findings were also reported to the IMO/IHO Harmonization Group on ECDIS, and precipitated more changes to the Performance Standards Document, up until its adoption by IMO (Res. A817) in November 1995 (IMO, Nov '95).

1.0 U.S. ECDIS TEST AND EVALUATION PROGRAM

1.1 INTRODUCTION

In 1990, the United States Coast Guard (USCG) was tasked with determining the potential of Electronic Chart Display and Information System (ECDIS) to improve safety of navigation. Provisional Performance Standards for ECDIS had recently been published by the International Maritime Organization (IMO) in 1989 (IMO, 1989). This standard was established to facilitate the worldwide development and utilization of ECDIS as a shipboard navigation system. These Provisional Performance Standards became a guide for the USCG to develop a comprehensive test and evaluation program. The goals of the program were to:

- determine the capabilities and limitations of current and prototype ECDIS devices for improving safety of navigation
- evaluate the adequacy of proposed ECDIS design and performance standards
- ensure that human factors considerations are incorporated into the design, operation, and performance of ECDIS

The USCG is involved in a variety of national and international ECDIS related projects designed to meet the goals of the USCG test and evaluation program (Alexander and Black, 1993). The tests listed below were specifically designed and carried out by the USCG Research and Development Center (R&DC) to assist in meeting these ECDIS program goals.

- OCTOBER 1990 INITIAL SEA TRIALS
- OCTOBER 1991 KINGS POINTER SEA TRIALS
- SEPTEMBER - OCTOBER 1992 SIMULATOR EXPERIMENTS
- JANUARY - APRIL 1993 BITTERSWEET & KINGS POINTER SEA TRIALS

The intention of this report is to provide a summary of the objectives, experimental design, instrumentation, and results for the above four tests. A more thorough description of the October 1991 KINGS POINTER Sea Trials can be found in Gonin, et. al. 1992. The September-October 1992 Simulator Experiment is described in much more detail in Smith, et. al. 1995 and also in the paper Gonin, et. al. 1994. More detailed information on the final test, the January-April 1993 BITTERSWEET & KINGS POINTER Sea Trials, can be found in Gonin, et. al. '95.

1.2 BACKGROUND

Due to significant technological advances in radionavigation, computer hardware and software, digital chart data, sensor integration, and geographical information system (GIS) technologies, great improvements in navigation are made possible. ECDIS combines these technologies and data to become a real-time GIS; this implies that ECDIS is a system capable of continuously

determining a vessel's position in relation to land, charted objects, aids to navigation, and unseen hazards. ECDIS has the potential to improve navigation accuracy, improve mariners' awareness of potentially dangerous situations, and reduce the workload on the bridge.

In the United States, three government agencies are responsible for providing essential services for the use of ECDIS.

- The U.S. Department of Defense is providing the Navstar Global Positioning System (GPS) for position input into ECDIS.
- The U. S. Coast Guard has installed a Differential GPS (DGPS) broadcast service which provides more accurate position information than GPS alone in harbor navigation areas.
- The Coast Survey (CS) Branch of the National Oceanic and Atmospheric Administration (NOAA) is expected to provide official digital chart data for ECDIS.

With these services, mariners will increasingly rely on automated radionavigation positioning and electronic chart displays. These new technologies will give mariners accurate, timely, and dependable data. The challenge lies in developing standards which will provide a clear and easy to understand display, on a system which is user-friendly.

In order to determine the effects of these new technologies on navigation performance, the USCG has had an active human factors research program for more than a decade. The program focused on the effectiveness of ECDIS-style integrated displays for the specific operation of harbor/harbor approach piloting, especially in reduced visibility. Systems have been examined both at sea (Cooper and Bertsche, 1981: Roeber, 1981) and on real-time-man-in-the-loop simulators (Gynther and Smith, 1988: Smith and Mandler, 1992). These reports describe important findings on the effectiveness of display features, the influence of positioning error on the effectiveness of these displays, and the influences of a RADAR overlay on piloting performance. These reports were the base from which the current effort was launched.

There are generally considered to be two categories for electronic chart-based navigation systems: ECDIS and Electronic Chart Systems (ECS). ECDIS is defined as a system which is compliant with the International Maritime Organization (IMO) Performance Standards for ECDIS, systems which are not “IMO compliant” are categorized as ECS. As the technology continues to improve and standards continue to be developed, manufacturers continually strive for systems which are IMO compliant (i.e., ECDIS). During the time period of each of the studies described in this report, the performance standards were in flux, and few manufacturers could keep up with the changes. Therefore the “ECDIS” employed in these studies were of the highest level of sophistication available at the time, yet, were only able to meet some of the IMO requirements.

2.0 OCTOBER 1990 INITIAL SEA TRIALS

Objective

The objective of the initial sea trials was to determine the minimal requirements for an ECDIS device that would increase navigation safety. The initial sea trial experiment was designed to develop the expertise and methodology needed for testing ECDIS. Commercially available ECDIS technology was evolving so rapidly that a prototype system designed specifically for these ECDIS evaluations could become obsolete too quickly. It became the goal of the USCG R&DC to concentrate on the design of an experiment which could be performed with any off-the-self ECDIS so that technology would not limit the evaluation.

2.1 EXPERIMENTAL DESIGN

Subjects

The pool of subjects consisted of one master and one cadet.

Method

A series of transits were made by one master and one cadet on an established route with predetermined turns and waypoints in a fairly confined waterway. The track was basically a zig-zag in the channel. Although a somewhat artificial route, it was intended to compress many turns in a short distance, so that differences in navigation performance could easily be seen. Deviation from intended track was monitored and recorded for the three types of navigation runs as illustrated in Table 2.1.1. These methods of navigation, with slight variations, were used in all the experiments performed with ECDIS. Traditional navigation and RADAR navigation were the baseline methods used to compare ECDIS navigation performance. Deviation from intended track was used to determine mariner performance (Table 2.1.2).

Table 2.1.1 Experimental Design Factors

Factors Controlled	**Levels**
1) Navigation Type	Traditional
	RADAR
	ECDIS

Table 2.1.2 Experimental Design Performance Measures

Objective Measures	1) cross track distance
Subjective Measures	None

2.2 INSTRUMENTATION

These harbor navigation tests were conducted onboard the United States Merchant Marine Academy (USMMA) T/V KINGS POINTER, a 150-foot (45-meter) ocean going tug, using the NavGraphic II - Electronic Chart System (ECS) from Trimble Navigation, USA (Table 2.2.1). At the time, this was one of the more capable ECSs commercially available.

Table 2.2.1 Instrumentation

Experimental Platform	T/V KINGS POINTER, a 150-foot (45-meter) ocean going tug
ECS Platform	NavGraphic II - Electronic Chart System (ECS), from Trimble Navigation, USA
	Features:
	raster scan digital chart data using a CD ROM for storage and access
	integrated GPS (primary) and LORAN-C (secondary) position sensors
	capable of waypoint navigation
	displays for course over ground (COG), speed over ground (SOG), cross track distance (XTD), latitude and longitude (lat/lon), and range and bearing
	capability of setting alarms (i.e. entering a mariner-determined danger area)
Comment	awkward user interface; difficult and non-intuitive navigation menu

2.3 RESULTS

Cross track data were analyzed and the results indicated that overall track keeping performance is improved while navigating with ECDIS. Both the cadet and master felt they had a better feeling for where they were in the route. They seemed to be able to anticipate turns more easily when using the ECDIS. At one point the cadet said, "Using the ECDIS is like playing a video game, just keep the vessel icon on the track line."

The results from this initial trial were encouraging, although there was still much to be done in determining the potential of ECDIS. In this trial only two subjects were used and they each performed the same run many times. As often happens in such a case, the later runs showed better results than the earlier runs; this is commonly referred to as "the learning effect." Additionally, the use of predefined turns and waypoints were an artificial constraint on the mariner. Solving some of these problems and improving upon the test methodology were part of the goals for the follow-on sea trials.

3.0 OCTOBER 1991 KINGS POINTER SEA TRIALS

Objective

With the completion of the initial sea trials, a solid foundation for testing and evaluating ECDIS was established. The objective was to conduct a more comprehensive set of trials in this follow-on experiment. This next experiment tested ECDIS performance standards, and the effect of ECDIS on navigation safety and mariner workload. Additionally, the state-of-the-art in ECDIS technology had moved ahead. Therefore, a more capable ECDIS device was used for the evaluation. This device was able to support configuration changes (i.e. graphics and alphanumerics-size, color, type and quantity), integration of a variety of sensors (i.e. GPS, DGPS, LORAN, speed, heading, depth, RADAR, etc.), and use vector based digital chart data (i.e. database of chart objects and attributes displayed on a screen).

3.1 EXPERIMENTAL DESIGN

Subjects

The subject pool consisted of 20 mariners: 4 pilots, 5 masters, 4 mates and 7 cadets.

Method

In order to help correct for the learning effects experienced in our initial trials, a larger pool of subjects and a more robust experimental design were used. Additionally, to make the experiment as realistic as possible, we had each mariner plot his/her own route around Rikers Island, NY.

The United States Merchant Marine Academy's ocean going tug, T/V KINGS POINTER, was used for the trials. This vessel and its location (i.e. near the East River in New York City in the vicinity of Rikers Island with its abundance of navigation aids such as buoys, lights, stacks, etc., and a sharp turn in the waterway) provide an ideal test platform/location to conduct navigation tests and evaluations in confined waterways.

A test matrix was developed which attempted to reduce some of the problems in the initial trials, as well as build on the areas that produced good results. Once again, cross track distance was used to measure performance. In this experiment, however, the use of an exit survey was added (Table 3.1.1).

Table 3.1.1 Experimental Design Performance Measures

Objective Measures	1) Cross Track Distance
Subjective Measures	1) Exit Survey

The experiment evaluated the performance of four different types of mariners, while executing three types of navigation runs, during day and night time transits, in west/south and north/east directions; during periods of good and poor visibility, in a confined waterway, using mariner developed routes. These Experimental design factors are illustrated in Table 3.1.2 and 3.1.3. Poor visibility was simulated by covering the bridge windows with opaque paper.

Table 3.1.2 Experimental Design Factors

Factors Controlled	**Levels**
1) Navigation Type	Traditional
	RADAR
	ECDIS
2) Time of Day	Day
	Night
3) Direction	West and South
	North and East
4) Visibility	Poor
	Good

Table 3.1.3 Test Matrix and Runs Performed

Run No.	**Direction**	**Navigation Method**	**Condition Visibility**	**Condition Time**	**Runs Performed**
1	A-B	TRADITIONAL	Good	Day	5
2	West/South			Night	2
3		RADAR	Poor	Day	2
4				Night	2
5		ECDIS	Good	Day	4
6				Night	0
7			Poor	Day	5
8				Night	2
9	B-C	TRADITIONAL	Good	Day	6
10	North/East			Night	2
11		RADAR	Poor	Day	2
12				Night	1
13		ECDIS	Good	Day	3
14				Night	0
15			Poor	Day	6
16				Night	2

A secondary goal of this sea trial was to evaluate some of the ECDIS functions and features proposed in the IMO Provisional Performance Standard for ECDIS (IMO, 1989). This task was accomplished by having each mariner fill out an evaluation after using the ECDIS. A compilation of the responses received from all experiments, along with other results and conclusions would be combined and used to develop the USCG response to IMO on the Provisional Performance Standard for ECDIS.

In order to ensure that there was a specific distinction between traditional and RADAR navigation for determining mariner performance, good and poor visibility was assigned to each respectively. Typically, a mariner uses traditional or visual piloting as a primary method of navigation in good visibility and uses the RADAR quite heavily in restricted visibility. Performing traditional navigation without the RADAR in restricted visibility is not feasible and performing RADAR navigation in good visibility is quite similar to traditional or visual piloting.

3.2 INSTRUMENTATION

The Precise Integrated Navigation System (PINS) 9000 was used as the ECDIS platform. This system uses vector chart data produced by its manufacturer, Offshore Systems Ltd (OSL), Canada. Features of the PINS 9000 are described in Table 3.2.1. The use of vector-based data,

Table 3.2.1 Instrumentation

Experimental Platform	T/V KINGS POINTER, a 150-foot (45-meter) ocean going tug
ECDIS Platform	Precise Integrated Navigation System (PINS) 9000, manufactured by Offshore Systems Ltd (OSL), Canada
	Features:
	vector-based digital charts data produced by its manufacturer, which allows for fast chart refresh and extensive "zooming" capabilities
	integration of ship's Gyro Compass and Differential Global Positioning System (DGPS)
	capable of waypoint navigation
	displays for course over ground (COG), speed over ground (SOG), cross track distance (XTD), latitude and longitude (lat/lon), and range and bearing
	capability of setting alarms (i.e. entering a mariner-determined danger area)
	two independent monitors; one on the bridge for navigation, the other in the chart room for monitoring
Comment	user interface advanced, allows for custom screens, and many sensor displays; navigation menu more user-friendly, but still non-intuitive.

allows for fast chart refresh and extensive "zooming" capabilities. This system also allows custom screens and many sensor inputs. This flexibility makes it an ideal tool for test and evaluation. Several screens were created with different alphanumeric and chart information taken

from the proposed IMO Provisional Performance Standard for ECDIS (IMO, 1989). This gave the mariner an opportunity to select a specific screen and gave us good feedback on the types of information mariners felt they needed on an ECDIS.

3.3 RESULTS

Two different approaches were used to analyze the data collected. The first approach analyzed the different skill levels and navigation methods (which included good and poor visibility) using all the cross track distance data. This approach created a cumulative frequency distribution curve for each set of cross track distance data. This provided a presentation of the proportion of observations that are less than or equal to the upper limit of the data set selected. Other descriptive statistics such as summaries of average (mean), standard deviation, minimum and maximum values were also calculated.

Next, after correcting for the high level of autocorrelation for the cross track distance data, Analysis of Variance (ANOVA) was performed on the remaining variables (west/south/north/ east direction and day/night transits).

Table 3.3.1 was created to summarize some specific values of cross track distance received from the Cumulative Distribution Function (CDF) of four categories of runs. These are all combined runs, all ECDIS runs, all traditional runs, and all RADAR runs. It can be seen from this table that the runs with ECDIS show by far the lowest cross track distance of all of the methods tested.

Table 3.3.1 Summary of Cumulative Distribution Frequencies of Cross Track Distance (deviation from intended track in meters) of 50% and 95% Points

	ALL RUNS		ECDIS		TRADITIONAL		RADAR ONLY	
	50%	95%	50%	95%	50%	95%	50%	95%
ALL SUBJECTS	15	76	**10**	**44**	26	86	22	114
PILOTS	15	91	**10**	**46**	37	95	20	158
MASTERS	15	91	**8**	**46**	26	107	20	93
MATES	17	58	**12**	**42**	25	57	32	90
CADETS	18	78	**12**	**42**	25	80	NOT TESTED	

3.3.1 Navigation Methods Compared

Mariner performance for each of the three types of navigation methods tested (i. e. ECDIS, RADAR, and traditional piloting) are plotted in Figure 1. There is a significant difference between mariners performing ECDIS navigation versus more traditional methods, mean (average) difference of almost 20 meters.

When using ECDIS, no significant difference in performance between the four experience levels

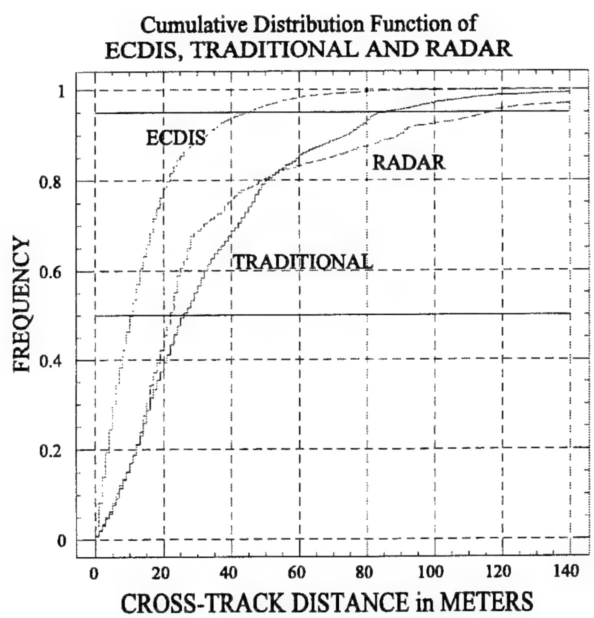


FIGURE 1 - ALL RUNS

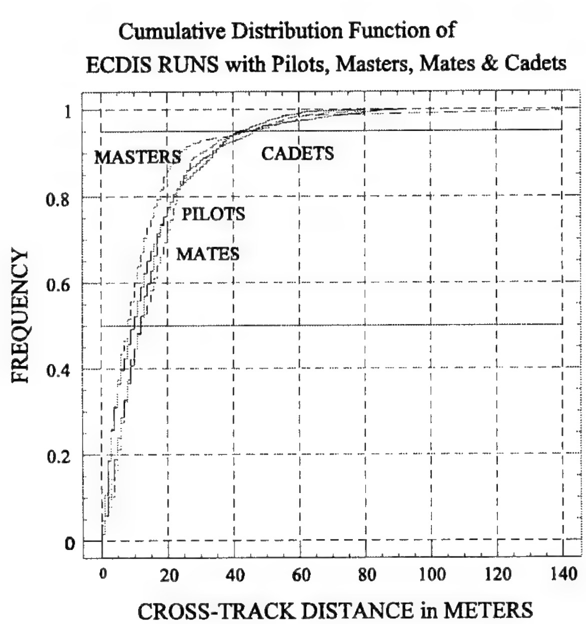


FIGURE 2 - ECDIS RUNS

of mariners was detected(see Figure 2). The difference in mean cross track distance between all four experience levels was 4.4 meters. With traditional navigation the difference between mean cross track distance was 12.6 meters and with RADAR only navigation the difference was 12.1 meters.

Figure 3 shows CDF of cross track distance of all experience levels performing traditional navigation. In this analysis the mates performed slightly better than the other three experience levels. After discussion with mariners and scientists, the general consensus was that mates were the most conscientious of all four groups because of their combination of recent training and experience.

Although helm commands were not part of the test, it was observed that the mates gave many helm commands to maintain track. Pilots, and to a lesser degree masters, knew that they were off track, but felt comfortable with their position when they were navigating by traditional methods. They felt it unnecessary to give a lot of helm commands to get back perfectly on track. Cadets, on the other hand, have very little experience, but a lot of training. Because of this inexperience, they were less able to anticipate

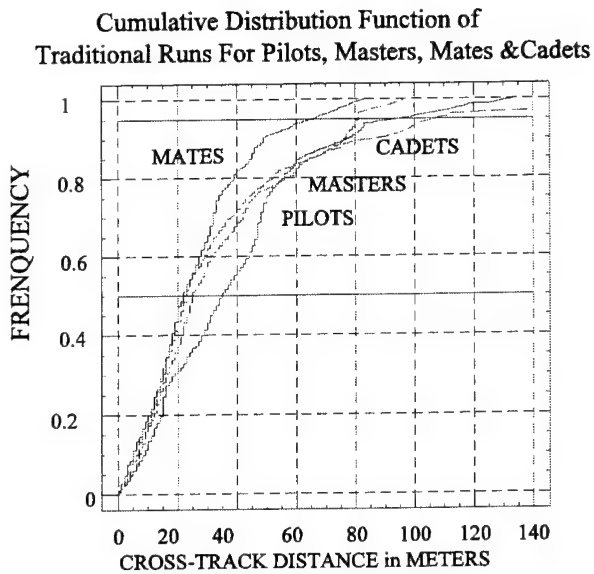


FIGURE 3 - TRADITIONAL RUNS

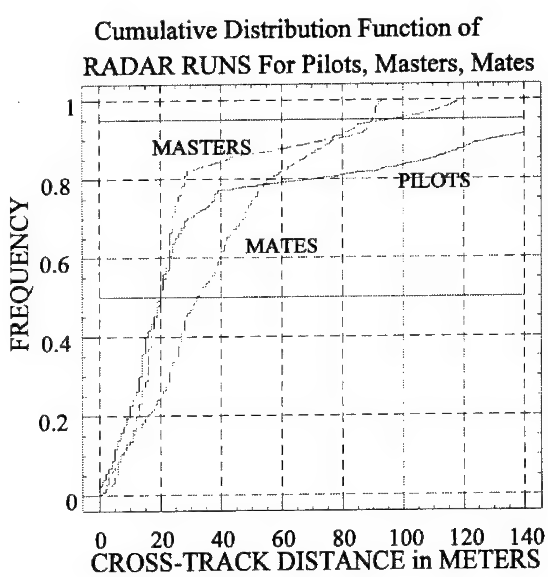


FIGURE 4 - RADAR RUNS

their new position. This resulted in many helm commands given in an effort to stay on intended track.

Figure 4 shows RADAR runs by mariner type. Cadets did not participate in this portion, as they were not considered to be experienced enough to navigate the ship with RADAR only. Much the same as in the runs with traditional navigation, there were significant differences between the three experience levels.

Masters performed slightly better than the pilots, mates, and cadets while navigating with ECDIS, as seen in Figure 2. They seemed to have a slight edge in shiphandling of the particular vessel, the T/V KINGS POINTER. The masters seemed to be able to anticipate turns better, more so than the pilots, who were accustomed to larger ships, and the mates who do not often perform shiphandling in confined waterways.

3.3.2 Track Keeping Performance

Preliminary analysis with the ANOVA method indicated that cross track distance tended to decrease with the run number. This may be due to learning effect, since some of the mariners performed the same run more than once under different conditions. A more thorough analysis showed that the main variable which explained variation in cross track distance

was navigation type. In general, mariners using ECDIS had significantly lower cross track distance than those using RADAR or traditional techniques. Also, those mariners who used traditional techniques performed better than those who used only the RADAR.

3.3.3 Day and Night Comparisons

Another variable which explains cross track distance variation, in conjunction with navigation type, is day vs. night. As was expected, the mariners tested during day runs performed better than those tested during night runs.

The interaction between navigation type and day vs. night is interesting. On day runs, mariners using ECDIS performed the best, with little performance difference between those using RADAR only and those using traditional methods. At night, mariners using ECDIS still performed the best, and those using traditional and RADAR methods performed considerably worse.

The direction of transit did not have any significant effect on navigation performance.

3.3.4 Responses from Evaluations

Evaluation forms were filled out by 16 of the 20 test subjects (four cadets did not respond). The evaluation contained 48 true/false, multiple choice and fill in questions.

A compilation of the results showed that the mariners felt differently about the number of chart windows displayed at one time: 45% wanted a two-chart windows, 36% called for a one-chart window, and 18% wanted a three-chart window. When asked about which chart orientation they would use the most, 93% said North-up. For most important sensor displays, the mariners chose: gyro, course made good, speed, and cross track distance. Some of the comments which were reported were concerns about having no traffic information (i.e. RADAR targets) integrated into the ECDIS, while others said ECDIS made the task of navigation more relaxing.

3.3.5 Resulting Contribution to ECDIS Performance Standards

The USCG IMO/IHO HGE representative for ECDIS standards development used the findings from these sea trials to develop a position paper on several of the ECDIS Provisional Performance Standards Issues. This position paper along with other Member Nations recommendations were combined to create an IHO/IMO HGE Draft Performance Standard for ECDIS (IHO/IMO, Sep 1992).

4.0 SEPTEMBER - OCTOBER 1992 SIMULATOR EXPERIMENTS

Objective

The objectives of the experiment were to examine several broad issues underlying the IMO Draft Performance Standard, for which the simulator was especially appropriate as a tool. The simulator makes it possible to examine the dynamic situation of route monitoring with a control that would be difficult or impossible at sea. The following four major issues were

addressed:

- <u>Contribution of ECDIS to the Safety of Navigation</u>. ECDIS should enhance safety by affording the mariner a more accurate knowledge of the ship's position, and its relation to a planned route and to potential hazards than is possible with conventional bridge procedures and a paper chart.

- <u>Reduction of Navigational Workload by ECDIS</u>. ECDIS can integrate information from a number of sensors, and can automate the primary and generally time-consuming navigation function of position fixing. These capabilities should reduce the mariner's workload. There is, of course, the implicit assumption that reduced workload also contributes to greater safety.

- <u>Chart Features and Navigational Functions on ECDIS</u>. At this early point in the development of ECDIS technology, there was no industry consensus about which electronic chart features and computer-based navigation functions would be needed by mariners. The simulator experiment allowed observation of mariners' use and selection of features and functions. This use was observed while mariners operated two systems under a variety of marine conditions.

- <u>Integration of RADAR Features on ECDIS</u>. The most highly integrated navigational system combines two plan view displays -- the electronic navigation chart and RADAR/automated RADAR plotting aid (ARPA) -- on one system. It was hypothesized that this integration would have positive effects on safety and workload.

4.1 EXPERIMENTAL DESIGN

Subjects

The six participants for the study included four masters (unlimited license), each with more than 20 years of experience, one chief mate and one second mate. During each week, each mariner received brief but formal training on the two ECDIS systems and ran through all the experimental scenarios in a different counter-balanced order.

Method

The test plan was intended to maximize the advantages of a simulator by selecting those issues most effectively and/or efficiently examined there. As is frequently done in simulator research, the workload was increased beyond realistic levels on the assumption that a high, but sustainable, workload increases the sensitivity of the performance measures. To ensure a high workload, each participating mariner made port arrivals and departures as the one officer alone on the bridge. In addition, no pilot came on board when the ship passed the pilot station. To keep the workload sustainable, the equipment consoles were arranged for "centralized control" to minimize movement around the bridge. A qualified helmsman was present in all scenarios.

As the single officer on the bridge, the subject mariner was responsible for navigation, collision

avoidance, and bridge management activities. The experimental scenarios were designed to be approximately equal in level of difficulty representing each of these three categories of activities. This scenario design is an example of the type of control that is possible on the simulator but not at sea.

The simulation tests consisted primarily of route monitoring in the relatively high risk coastal and harbor/harbor approach phases of navigation during vessel arrivals and departures from port (Federal Radionavigation Plan, 1990). Each mariner spent a full week on the simulator, making harbor transits with ECDIS configurations that differed in such critical features as position updating mode and RADAR overlay.

The primary controlled factor was the method of navigation available to the watchstander in a given scenario (Table 4.1.1). The conventional choices for navigation were: position fixing on the paper chart, RADAR/ARPA, and visual piloting. In two "baseline" scenarios, only these conventional methods were available. In the remaining scenarios, one of the commercial systems was added to the bridge in one of three modes:

- ECDIS with automatic position updating and RADAR features (Positioning was to an accuracy of five meters or better. Mariners were told that differential Global Positioning System was in use.)
- ECDIS with automatic position updating and <u>no</u> RADAR features
- ECDIS <u>without</u> automatic position updating (and with instructions to update manually)

In addition, the experimental scenarios were designed to vary in visibility, route, and harbor.

Table 4.1.1 Experimental Design Factors

Factors Controlled	Levels
1) Navigation Type	Traditional Navigation: visual piloting, paper chart, RADAR/ARPA
	ECDIS <u>with</u> automatic position updating and RADAR features (Positioning was to an accuracy of five meters or better. Mariners were told that differential Global Positioning System was in use.)
	ECDIS <u>with</u> automatic position updating and <u>no RADAR features</u>
	ECDIS <u>without</u> automatic position updating (and with instructions to update manually)
2) Visibility	Unlimited
	Clear
	Reduced to one nautical mile
3) Route	Inbound
	Outbound
4) Harbor	New York
	San Francisco

A variety of human factors techniques for measuring performance and operator reactions were used (Table 4.1.2). These included: measures of workload using the National Aeronautics and Space Administration's Task Load Index - NASA TLX (Hart and Staveland, 1988), situational awareness, ratings of safety and preference, and extensive questionnaires.

Table 4.1.2 Experimental Design Performance Measures

Objective Measures	1) Cross Track Distance
	2) Situational Awareness
	3) Ratings of Safety and Preference
Subjective Measures	1) Extensive Questionnaires
	2) NASA TLX

4.2 INSTRUMENTATION

The experiment was run at MSI/CAORF in Kings Point, New York. This simulator has a realistically equipped full mission bridge and a considerable history of human factors and ship control research. The simulator capabilities include sophisticated ship models, harbor data bases, observational and data collection methods.

During the selection of ECDIS devices, the USCG chose two commercially available ECDIS units which most closely met the requirements for this evaluation (Table 4.2.1).

Table 4.2.1 Instrumentation

Experimental Platform	Marine Safety International/Computer Aided Operations Research Facility (MSI/CAORF) in Kings Point, New York
ECDIS Platform	1) Precision Integrated Navigation System - VME (PINS-VME): Offshore Systems Ltd (OSL), Canada - Comment: provided proven RADAR overlay. 2) Disk Navigation System (ROB), Robertson Marine Systems Inc. , Norway - Comment: electronic chart system more IMO compliant.
	Common Features:
	vector based digital charts data produced by its manufacturer, which allows for fast chart updating and extensive "zooming" capabilities
	position sensors used - ship's gyro compass and Differential Global Positioning System (DGPS)
	waypoint navigation capability
	displays for course over ground (COG), speed over ground (SOG), cross track distance (XTD), latitude and longitude (lat/lon), and range and bearing
	capability to set alarms (i.e. entering a mariner determined danger area)
	integrated RADAR overlay
Comment	user interface advanced, allows for custom screens and display of sensor information; navigation menu very user-friendly and intuitive

These two systems differed from each other in their treatment of such features as chart presentation, RADAR overlay and user interface. The Offshore Systems Ltd.'s (OSL), Precision Integrated Navigation System - VME (PINS-VME) provided a proven RADAR overlay capability. The Robertson Marine Systems, Inc.'s Disk Navigation System (ROB), most closely conformed to the IMO Provisional Performance Standards (IMO, 1989) for display presentation and functions. Both systems were interfaced with the MSI/CAORF simulator.

4.3 RESULTS

4.3.1 Primary Method of Navigation

The primary method of navigation that each mariner used for each identifiable segment of the transit was reported by the mariner after each scenario. The assumption was that the mariner's selection of method would reflect his view of the best combination of safety and workload for the conditions. The results are summarized in Table 4.3.1 for the harbor/harbor approach phase of navigation, with its high risk and high workload.

The test subjects rarely reported using the paper chart for position fixing. Instead, during conventional bridge conditions (i.e., no ECDIS available), visual piloting and RADAR/ARPA were reported to have been used. When ECDIS with automatic updating of position was available, it was reported to be the predominant method of navigation. Without automatic updating of position and with the requirement to update manually, ECDIS lost its preferred status.

Table 4.3.1 Proportion of Total Segments for Which Each Method of Navigation Was Reported as Primary in Harbor/Harbor Approach Navigation

BRIDGE CONDITIONS	PLOTTING/ PAPER	RADAR/ ARPA	VISUAL PILOTING	ECDIS	TOTAL # SEGMENTS
Conventional Bridge	0.03	0.25	0.73	NA	40
ECDIS Auto Positioning	**0.00**	**0.15**	**0.18**	**0.67**	**79**
ECDIS no Auto Positioning	0.05	0.61	0.28	0.05	18

4.3.2 Safety Measured by Accuracy of Track Keeping

Safety of navigation has been measured in simulator research (Kaufman, 1985; Schryver, 1985) and in sea trials (Gonin and Crowell, 1992) by cross track distance from a planned route. Although no special instructions to keep the ship close to the line were given in this experiment, it was hypothesized that ECDIS would increase safety by reducing cross track distance. At some critical points, such as approaches to bridges or to major turns, the availability of ECDIS with automatic positioning resulted in substantial reductions in mean cross track distances.

4.3.3 Workload Measured by Time Spent and by Mariner's Ratings

Workload was measured after each scenario by asking the mariner what proportion of his time was spent on navigation, collision avoidance and bridge management. A self-reported workload on each of these three tasks was also administered using the NASA-TLX (Hart and Staveland, 1988).

A summary of the findings are presented in Table 4.3.2. The availability of ECDIS with auto-positioning decreased both the mean workload for navigation and the mean reported proportion of time spent on navigation, as compared to that measured for conventional bridge procedures. The necessity of manually updating position increased the navigation workload and the proportion of time spent on navigation. Workload was increased over that for both the conventional bridge and ECDIS with automatic positioning.

Table 4.3.2 Mean Navigation Workload and Reported Distribution of Mariner's Time

BRIDGE CONDITIONS	NAVIGATION WORKLOAD	NAVIGATION	COLLISION AVOIDANCE	BRIDGE MANAGEMENT
Conventional Bridge	52	0.46	0.33	0.21
ECDIS Auto Positioning	**36**	**0.37**	**0.41**	**0.21**
ECDIS **NO** Auto-Positioning	63	0.49	0.34	0.17

4.3.4 Time Spent on Navigation Versus Time Spent on Collision Avoidance

Table 4.3.2 also shows that with the decrease in proportion of time spent on navigation using ECDIS with automatic positioning, there was a corresponding increase in the proportion of time spent on "look out" and on collision avoidance. *In the mariner's view, this shift represented an increase in safety.*

Navigation workload and the proportion of time spent on navigation were positively and significantly correlated with each other. Navigation workload and the proportion of time spent on collision avoidance were negatively and significantly correlated.

4.3.5 Feature and Function Use

The use of chart features and navigation functions on ECDIS was examined in a number of ways.

- experimental observers watched on video monitors and tallied features and functions enabled on the ECDIS systems by the mariner
- questionnaires after each scenario contained checklists for reports of what had been used and what was wanted
- a final questionnaire contained a checklist asking the mariner to recommend what should be available

The results obtained with this final measure showed that only a relatively small set of features were recommended by a majority of the mariners as "display always." The mariners instead showed a clear preference that all objects commonly found on a navigation chart should be available at user's option. Mariners indicated that although a simple display is preferred for the monitoring task, other more detailed information should be readily available.

Table 4.3.3 -Display Information Most Preferred by Mariners

FEATURES	DISPLAY ALWAYS	AT USERS'S OPTION
Charted Features		
Coastline/Landmass	100%	0%
Fixed Aids to Navigation	100%	0%
Floating Aids to Navigation	100%	0%
Federal Channel Lines	67%	33%
Navigation Lanes/Fairways	67%	33%
Pilot Areas	67%	33%
Indication of Isolated Dangers	67%	33%
ECDIS Generated Features		
Ownship Outline	83%	17%
Display Planned Trackline	83%	17%
Navigation Fault Alarms (i.e., GPS down)	100%	0%

4.3.6 Results on the Use of RADAR Overlay

No significant differences were found between ECDIS with and without RADAR features, or between ECDIS with the complete RADAR video and ECDIS with targets only. Mariners felt that RADAR integration should be a valuable addition to ECDIS. The systems they used, however, were not good examples of how RADAR integration should work. The principal drawbacks mentioned were an overly cluttered screen and incomplete ARPA information that did not allow them to depend on the ECDIS for both navigation and collision avoidance.

5.0 JAN - APR 1993 BITTERSWEET & KINGS POINTER SEA TRIALS

Objective

Since these tests were meant to be an at-sea verification of the simulator results, the objectives of the research remained very similar.

- Contribution of ECDIS to the Safety of Navigation
- Reduction of Navigation Workload by ECDIS
- Chart Features and Navigation Functions on ECDIS
- Integration of RADAR Features on ECDIS.

5.1 EXPERIMENTAL DESIGN

Subjects

There were two pools of subjects for these tests. For the first part of the experiment, all of the BITTERSWEET's seven qualified Officers of the Deck (OOD's) participated, three senior watchstanders and four junior watchstanders. In the second part, thirteen experienced mariners participated: four pilots, four masters and five mates.

Method

The experiment consisted of two parts. The first part was performed aboard the USCG Cutter BITTERSWEET. It allowed for a direct comparison of navigational performance on an ECDIS equipped bridge with traditional navigation using the paper chart. The conceptual approach to this at-sea test was to examine baseline performance with the mariner using traditional techniques: a paper chart, RADAR/ARPA, and visual piloting. Then, ECDIS, in two different modes, was used to examine its effect (i.e., the changes from baseline performance). In addition, such variables as area of transit, visibility, time of day and mariner were evaluated.

The second part of the experiment was performed aboard the T/V KINGS POINTER. This part of the experiment was designed to gather additional data and information in specific areas which did not provide enough conclusive evidence in the first part of the experiment aboard the USCGC BITTERSWEET.

A variety of human factors techniques for measuring performance and operator reactions were used. These included measures of workload such as the U.S. National Aeronautics and Space Administration's Task Load Index (NASA TLX, 1988) ratings of safety and preference, comprehensive user questionnaires and interviews (Table 5.1.1).

Tests scenarios were performed in Buzzards Bay and Narragansett Bay. These test included operations in coastal and confined waterways during periods of good and poor visibility, and during day and night transits with low and moderate traffic density using various navigation methods (Table 5.1.2).

Table 5.1.1 Experimental Design Performance Measures

Objective Measures	1) Cross Track Distance
	2) Course made good (CMG)
	3) Gyrocompass heading
	4) Speed Over Ground (SOG),
	5) Speed Made Good (SMG),
Subjective Measures	1) Extensive Questionnaires
	2) NASA TLX

Table 5.1.2 Experimental Design Factors

Factors Controlled	**Levels**
1) Navigation Type	ECDIS with RADAR overlay - this mode was chosen to allow for evaluation of the IMO Draft Performance Standard for the integration of RADAR into ECDIS.
	ECDIS without RADAR overlay - this mode was chosen since it would most likely be the base configuration for ECDIS and would allow for evaluation of many mariner-ECDIS interface issues.
	Traditional navigation with paper chart - this mode will be the baseline from which to compare navigational performance with performance using ECDIS.
	ECDIS without automatic position updating and with instructions to update manually
2) Visibility	Good - greater than one mile visibility
	Poor - less than one mile visibility or simulated zero visibility (i.e. covered bridge windows).
3) Time of Day	Day
	Night
4) Area of Operation	Coastal
	Harbor/Harbor Approach

Table 5.1.3 - Sea Trial Scenario Matrix

Test No.	Test Area	Navigation Method	Condition Visibility	Condition Time	Number of Runs Performed
1	A COASTAL	ECDIS w/RADAR	Good	Day	2
2				Night	0
3			Poor	Day	2
4				Night	2
5		ECDIS wo/RADAR	Good	Day	3
6				Night	2
7			Poor	Day	2
8				Night	1
9		TRADITIONAL	Good	Day	1
10				Night	1
11			Poor	Day	2
12				Night	3
13	B HARBOR/ HARBOR APPROACH	ECDIS w/RADAR	Good	Day	2
14				Night	0
15			Poor	Day	2
16				Night	2
17		ECDIS wo/RADAR	Good	Day	2
18				Night	2
19			Poor	Day	3
20				Night	2
21		TRADITIONAL	Good	Day	3
22				Night	1
23			Poor	Day	1
24				Night	2
NOTE: Test scenario matrix was intended to be performed twice.					TOTAL = 43

5.2 INSTRUMENTATION

5.2.1 Test Vessel - USCGC BITTERSWEET

Sea trials were conducted during January - February 1993 aboard the USCG Cutter BITTERSWEET (WLB-389). This 180' (55m) ship was built in 1944, with a 37' (11.3m) beam, 13' (4m) draft, and 1025 dead weight ton (dwt) displacement. This vessel was particularly suited

for test and evaluation of ECDIS because of the crews' familiarity with advanced shipboard navigation systems such as GPS, differential GPS(DGPS), Laptop Automated Aids Positioning System (LAAPS), and Electronic Chart Systems (ECS) (Alexander and Quinn 1992).

Normal ship's complement onboard USCGC BITTERSWEET is 45 enlisted personnel and seven officers. During the trials, there were seven qualified Officers of the Deck (OOD). Six were commissioned officers, and one first class petty officer quartermaster. In terms of experience, there were three senior watchstanders and four junior watchstanders.

5.2.2 Test Vessel - T/V KINGS POINTER

A new T/V KINGS POINTER was received by the USMMA from the Navy in 1992. This training ship is the former U. S. Naval Ship CONTENDER (T-AGOS 2) built in 1984. This vessel has a overall length of 224' (67m), beam of 43' (13m), draft of 15' (4.5m) and dead weight displacement of 2,250 tons. The location of this vessel in the mouth of New York's East River in Long Island Sound makes an ideal area for coastal and harbor transits. A total of 11 mariners (5 mates, 4 masters and 2 pilots) from the USMMA and nearby State University of New York Maritime College participated in the experiment as well as two pilots from the Northeast Pilots Association.

5.2.3 Test Equipment

The Offshore Systems Limited (OSL) Electronic Chart Precise Integrated Navigation System (ECPINS) was the primary ECDIS used for the sea trial evaluation of the IMO/IHO ECDIS Draft Performance Standard. With the exception of implementing the new colors and symbols recently developed by an IHO Colors and Symbols Working Group, this Canadian-manufactured ECDIS system was nearly-compliant with the current IMO Draft Performance Standard published by HGE 13 in September 1992 (IMO/IHO HGE 1992).

In order to give the watchstanders an opportunity to learn about ECDIS, the PINS 9000 manufactured by Offshore Systems Limited (Canada) was installed aboard USCGC BITTERSWEET in January of 1992 and used by the mariners for 11 months. In December 1992, a new Offshore Systems Limited ECDIS called the Electronic Chart Precise Integrated Navigation System (ECPINS) was installed specifically for this evaluation. Two months later, the same version of ECPINS was installed aboard the T/V KINGS POINTER. Also, at that time, two other ECDIS devices were installed; the van Rietschoten en Houwens (R&H) Hydraut Electronic Chart (EC) Series and Atlas Electronik ATLAS 9800 ECDIS. (Table 5.2.1)

Table 5.2.1 Instrumentation

Experimental Platform	**A)** USCG Cutter BITTERSWEET (WLB-389) **B)** T/V KINGS POINTER (formerly CONTENDER: T-AGOS 2)
ECDIS Platform	**1)** Electronic Chart Precise Integrated Navigation System (ECPINS) : Offshore Systems Ltd (OSL), Canada (Installed on Platform **A and B**) **2)** van Rietschoten en Houwens (R&H) Hydraut Electronic Chart (EC) Series (**B Only**) **3)** Atlas Electronik ATLAS 9800 ECDIS (**B Only**).
	Features:
	1, 2 & 3) vector based digital charts; chart data produced by its manufacturer, which allows for fast chart refresh, and extensive "zooming" capabilities.
	1, 2 & 3) used the ship's gyro compass and Differential Global Positioning System (DGPS)
	1 & 2) capable of waypoint navigation
	1, 2 & 3) displays for course over ground (COG), speed over ground (SOG), cross track distance (XTD), latitude and longitude (lat/lon), and range and bearing
	1 & 2) capability of setting alarms (i.e. entering a mariner-determined danger area)
	2) capability to input range and bearing from objects for position checking
Comments	**2)** IHO standard chart data, excellent detail and representation of chart information
	1 & 2) user interface advanced, allows for custom screens, and integration of many sensor displays; menu structure user-friendly, and somewhat intuitive
	1) good integrated RADAR Overlay
	3) excellent RADAR picture with full RADAR/ARPA functionality

5.3 RESULTS

5.3.1 Performance Measures and Data Analysis

Performance measures and data analysis procedures were developed to determine the effect of ECDIS on navigation safety, and what ECDIS features and functions were essential to insuring navigation safety and efficiency. Navigation safety was directly addressed by the use of measures of cross track distance and mariner performance. Navigation safety and the efficiency of ECDIS were indirectly addressed by measuring the mariner's workload. The question of what ECDIS features and functions were essential to safe and efficient navigation was addressed by:

- recording the mariners use of ECDIS
- recording the features/functions the mariners sought (when not available on the ECDIS)

- obtaining the mariner's expert opinions regarding both general and specific aspects of the design and use of ECDIS

5.3.2 Effects on Safety and Workload

The experiment was designed to test the hypotheses that ECDIS would reduce the mariner's workload for navigation. With more available time and attention for other mariner functions, an indirect benefit should be increased safety. Using the NASA TLX, mariners were asked to rate workload after each run and to report the proportion of time spent performing navigation tasks, collision avoidance tasks, and bridge management tasks.

As shown in Table 5.3.1, when using ECDIS with RADAR overlay, the average workload reported by the mariner was the lowest. Additionally, the mariner spent a smaller proportion of his time on the navigation task, leaving more time to spend on the higher risk collision avoidance task. Compared to more traditional means of navigation, the use of ECDIS can significantly reduce navigation workload.

Table 5.3.1 - Navigation Workload and Distribution of Mariner's Time

Bridge Conditions	**Navigation Work Load**[a]	**Proportion of Time**[b]		
		Navigation	**Collision Avoidance**	**Bridge Management**
Traditional Bridge[c]	29	65	23	12
ECDIS	22	63	24	13
ECDIS w/RADAR Overlay[c]	**17**	**61**	**26**	**13**

Notes
a. Mean mariner rating of navigation workload using NASA-TLX
b. Mean mariner report of proportion of time spent on: navigation, collision avoidance, and bridge management.
c. Workload measure during navigation with ECDIS using RADAR Overlay is statistically different from traditional bridge at 0.05 level

5.3.3 Display Features

The IMO/IHO Draft Performance Standard for ECDIS 1992 (Draft Performance Standard) defines three subcategories of information display for the ECDIS.

o *Base Display*
"The permanent level of display information that would be required at all times, in all geographic areas, and under every circumstance. Not intended to be sufficient for safe navigation; the mariner is expected to add System Electronic Navigational Chart (SENC) information as required for the situation at hand."

o *Standard Display*
"The level of display information available when a chart is first displayed, which, depending on the needs of the mariner, can be modified; but which is always accessible again by a single operator action."

o All Other Information
"Any information which the mariner uses to navigate which isn't covered by the previous two categories."

The participating mariners were given a list of seventy-nine chart features, including the chart features that the Draft Performance Standard requires for *base* and *standard display*. The tabulated responses are discussed in the next section.

Base Display

For the *base display*, the Draft Performance Standard list of features is more comprehensive than that chosen by the mariners. Figures 7 and 8 show three lists of features. The top right area of the figures, lists the features the Performance Standard recommends, but were not selected by the mariner. The top left area, lists the features the mariners wanted, but were not included in the Performance Standard. The bottom area of the figures, lists those features common to both the mariner and the Performance Standard. Figure 7 illustrates, four out of the five features (80%) are common features chosen by the mariner and are included in the Performance Standard. Three features are included in the *base display* of the Performance Standard but were not selected by the mariner. Fixed and floating aids to navigation, the only feature chosen by the mariners not on the Draft Performance Standard *base display* list, is a feature of the Draft Performance Standard's *standard display*.

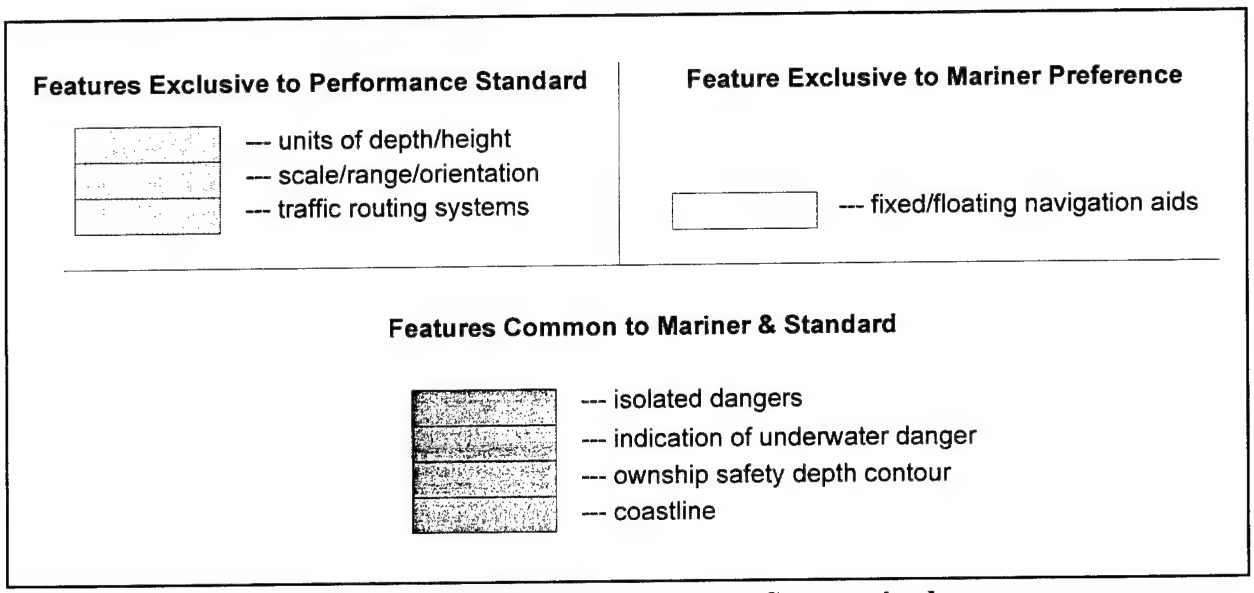


Figure 7 - *Base Display* Features Summarized

Standard Display

For the *standard display*, the mariners proposed a larger list of features than the Draft Performance Standard. In the *base display*, the smaller list was for the most part (86%), a subset of the larger. The Draft Performance Standard's *standard display* included two features not found in the mariner preference list: visual and RADAR conspicuous features, and indication of

cautionary notices (See Figures 8). It is interesting to note that, of the features found exclusively on the mariner preference list, half were full text cautionary and/or information notices. This seemed to indicate that perhaps mariners had selected the cautionary notes which they found most useful to be displayed in full, instead of the more general, less informative *indications* of such notices required by the Draft Performance Standard.

Additionally, four ECDIS functions: ownship outline, heading/beam bearing, cursor mark, and display planned track were selected by the mariner to be available in the *standard display* (i. e. these are not available on a paper chart). This tends to bear out the findings from the rest of the study, which indicate that the mariners felt such ECDIS features were an aid to navigation.

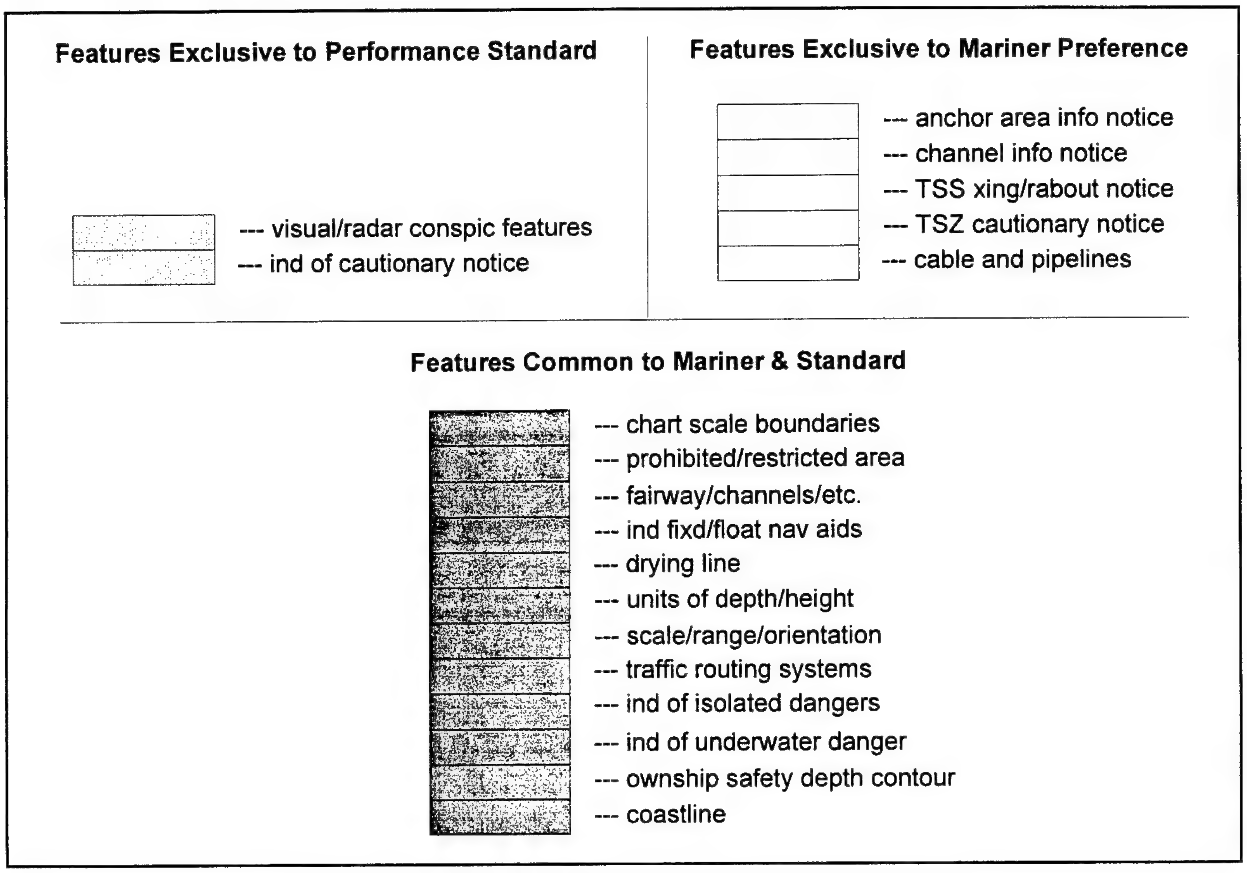


Figure 8 - *Standard Display* Features Summarized

5.3.4 Exit Interview on Display Features

The mariners were also given an exit survey which asked questions dealing with ECDIS functionality beyond the chart features displayed. Some interesting results are reported here.

An overwhelming majority (92%) of the mariners felt that ECDIS would be useful as a simulation/training tool. Although, they were split (58% vs 42%) on whether ECDIS could function as primary navigation tool. Most of the mariners the training they received was not

enough. They also reported that special training on the ECDIS would be necessary, similar to RADAR training.

Most mariners felt that North-up was the best default chart orientation for route planning, open ocean passage, coastal transit, harbor approach, and heavy traffic. However, the ability to switch from one orientation to another seemed to be a popular feature. It is also not surprising that a majority of the mariners reported that ECDIS symbols should always look the same as paper chart symbols.

In the discussion of warnings, the mariners prefer both audible and visual alarms to be given in most cases of likely danger (i.e., detection of possible collision/grounding, depth less than safety depth contour), or the loss of position, speed or other essential sensor information. For warnings of cross track error and entering a fishing ground or restricted area, the mariners reported that visual alarms were sufficient.

5.3.5 Statistical Analysis of Test Factors

In the initial set of statistical analysis, using the complete data set, only *navigational method* had a significant impact in improving navigational performance. Next a second set of statistical analysis was performed using only the data from the ECDIS runs, differentiating between those with and without RADAR overlay. In these second tests both *visibility* and the presence of a *RADAR-overlay* were significant in improving navigational performance.

The test was conducted during typical New England January weather. From these tests, it seems quite clear that ECDIS and ECDIS with RADAR-overlay have a positive impact on navigational performance across all types of visibility, times of day, and operators. This is encouraging, not just for the proponents of ECDIS, but for all mariners.

As one of the few studies providing empirical at-sea evidence to determine the impact of ECDIS on navigational performance, we are encouraged that our findings seem to corroborate the findings of similar studies at sea (Gonin and Crowell, 1992) and at ship simulator facilities (Smith, et. al, 1995, and Grabowski, et. al, forthcoming).

6.0 GENERAL CONCLUSIONS

The tests and experiments discussed in this report explored a progression of questions about Electronic Chart Display and Information Systems. We began with the simple questions explored in the first two sea trials: *Does ECDIS have an impact on overall track keeping performance? What are the effects of ECDIS on the navigational performance of mariners with different experience levels?* These questions lead to more complex experimental designs of the simulator experiments in 1992 and the 1993 sea trials.

Results of 1990 sea trials and the 1991 KINGS POINTER trials show that ECDIS *did* significantly improve overall track keeping performance, and that there were *no significant differences* in navigational performance between mariners with varying levels of experience *when navigating with ECDIS.* With these results, we can certainly answer the question: *"Is*

ECDIS an aid to navigation?", in the affirmative. The ECDIS, by creating a real-time visualization of the ship's position in relation to its surroundings, aids the mariner. This provided important groundwork for the follow-on experiments.

The objectives of the 1992 simulator experiments, as well as the 1993 sea trials were to examine several broad issues underlying the IMO Draft Performance Standards. The major findings of these trials are discussed here, segmented by issue.

Contribution of ECDIS to the Safety of Navigation

ECDIS **with automatic positioning** *decreased the mean cross-track distance* to approximately one third of what it was with conventional methods. The use of ECDIS during route monitoring can provide equivalent or greater safety than that provided by the use of the paper chart and more traditional methods of navigation. Three mechanisms which provide this safety were identified:

- cross-track distance from the planned route is decreased,
- mariners of all skill levels can perform track keeping more accurately and efficiently,
- an increased proportion of the mariners time is spent on "look out" and collision avoidance.

These findings, that ECDIS supports more accurate ship control and allows more time to be spent on non-navigation tasks, agrees with simulator evaluations of the use of automation for "one man bridge" operations (Schuffel, Boer, and van Breda, 1989). In a time where increased tonnage on the water and the related safety issues are a heated topic of discussion, these results show ECDIS can give the mariner more time for such tasks as lookout and collision avoidance, when they are most important. It must be made clear that these results are only true in the case of **ECDIS with automatic positioning**. It was shown in these sea trials that in the case of a failure of the automatic positioning, necessitating **manual positioning of ECDIS**, cross-track distance is increased and ECDIS loses its advantage in track keeping accuracy.

Reduction of Navigational Workload by ECDIS

In addition to measures of cross-track distance, the mariners were asked to report on their perceived workload with and without the ECDIS present, and in some cases with and without RADAR overlay. The results show, as was suspected from the reduction in cross track distance discussed above, mariners reported that ECDIS **with automatic positioning** *decreased both the mean workload for navigation and the mean reported proportion of time spent on navigation.* It was also shown that with the decrease in proportion of time spent on navigation using ECDIS with automatic positioning, there was a corresponding increase in the proportion of time spent on look out and collision avoidance. *In the mariners' view, this shift represented an increase in safety.*

- Only, in the later at-sea trial when using ECDIS with advanced RADAR integration technology, did the average workload reported by the mariner become the lowest, as compared to when the mariners had an ECDIS with more primitive (i.e. older) RADAR overlay.

- Overall, when compared to more traditional means of navigation, the use of ECDIS with automatic positioning can significantly reduce navigation workload. This in turn will give the mariner more time to devote to the more difficult tasks of look out and collision avoidance.

- Once again the necessity of manually updating position increased the navigation workload and the proportion of time spent in navigation.

Chart Features and Navigational Functions on ECDIS

Only a relatively small set of features, (which corresponded very closely with the "*base display*" in the Draft Performance Standards for ECDIS) were recommended by a majority of the mariners to be displayed always. The larger set recommended to be available at users option, corresponded very closely with the "*standard display*" in the Draft Performance Standards for ECDIS.

The mariners did, however, point out some areas where the Draft Performance Standard seemed to be lacking:

- the *base display*, or at the very least the *standard display*, should require a symbol for ownship's position.
- the Draft Performance Standard needs to be more specific about when and how warnings of system failures should be presented.

It should be noted, that along with the *base* and *standard displays*, the participating mariners indicated a need for an immediate and easy reference to a much larger set of features and functions in the more static mode of route planning. This capability would be similar to a conventional geographical information system (GIS), which provides much more extensive information for reference.

Integration of RADAR Features on ECDIS

Although mariners in the 1992 Simulator Experiments reported that RADAR integration should be a valuable addition to ECDIS, there were no significant differences found in ECDIS with and without RADAR features. This is most likely because the mariners reported that the examples that they saw were not satisfactory. The principal draw-backs mentioned were an overly cluttered screen and incomplete ARPA information. This became an important issue in the 1993 sea trials, with the advances in technology allowing a better exploration of this issue.

In the 1993 at-sea tests, as the advances in technology allowed a truer representation of RADAR integration, there was a decrease in workload when using ECDIS with RADAR overlay as compared to traditional methods of navigation. The comments and concerns on collision avoidance expressed by most of the mariners in these studies emphasize the need to integrate ECDIS with RADAR. Mariners indicated a preference for an integrated ECDIS/RADAR/ ARPA device with full capabilities for navigation and collision avoidance. This integrated system would have to be completely flexible in terms of which information is

available at a particular time.

6.1 FUTURE CONTRIBUTIONS OF ECDIS

The implications and impact of ECDIS on the maritime community are enormous. Expected benefits of ECDIS include improvements in navigation safety and increased shipping efficiency; all of which mean dollar savings to national marine administrations and shipping companies. Standards which describe how ECDIS must perform, what type of chart data it must use, and how this data are to be displayed, have just been finalized. After many years of international effort, both government and private, these standards are being adopted and will be held frozen as specified in Table 6.1.1. Dollar savings can only be realized if manufacturers begin to build systems which meet all these ECDIS standards.

Table 6.1.1 Status of IMO Compliant ECDIS Standards

IMO COMPLIANT ECDIS STANDARDS	DATE
IMO Performance Standard for ECDIS	Nov 1995
IHO S57 IHO Transfer Standard for Digital Hydrographic Data (Edition 3) (note: to be held frozen for four years)	Nov 1996
IHO S-52 Specifications for Chart Content and Display Aspects of ECDIS (Edition 5) Appendix 1 Guidance on Updating the ENC (Edition 3) Appendix 2 Colours and Symbols Specifications for ECDIS (Edition 4) Appendix 3 Glossary of ECDIS Terms (Edition 3) (note: all of the above to be held frozen for four years)	Dec 1996 Jan 1997 Mar 1997 Jun 1997
IEC Operational and Performance Requirements Methods of Testing and Required Test Results for ECDIS (10th Draft Nov 1996)	Final Fall 1997

With ECDIS standards complete, maritime administrations should begin the process of testing, certifying, and type approving these systems. Requirements and procedures for training and certifying mariners in the use of these systems should also begin quickly. Hundreds of systems, claiming to be nearly IMO compliant ECDISs are out onboard vessels now (e.g. including the USCG Juniper Class Buoy Tender). Regulations and carriage requirements should be established to insure the proper and appropriate use of these systems. A national infrastructure to support ECDIS is needed. One key element to this infrastructure is the availability of IHO compliant data and the mechanism to provide electronic chart updates to the users. It is only with a proper infrastructure to support ECDIS can maritime administrations take full advantage of the safety and economic benefits ECDIS can bring to their countries.

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